

# Cosmic Birefringence Fluctuations and Cosmic Microwave Background $B$ -mode Polarization

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Recently, BICEP2 measurements of the cosmic microwave background (CMB)  $B$ -mode polarization has indicated the presence of primordial gravitational waves at degree angular scales, inferring the tensor-to-scalar ratio of  $r = 0.2$  and a running scalar spectral index. In this *Letter*, we show that the existence of the fluctuations of cosmological birefringence can give rise to CMB  $B$ -mode polarization that fits BICEP2 data with  $r < 0.11$  and no running of the scalar spectral index. Thus, it might be too hasty to conclude that many inflation models with small  $r$  are ruled out based on BICEP2 result.

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The spatial flatness and homogeneity of the present Universe strongly suggest that a period of de Sitter expansion or inflation had occurred in the early Universe [1]. During inflation, quantum fluctuations of the inflaton field may give rise to energy density perturbations (scalar modes) [2], which can serve as the seeds for the formation of large-scale structures of the Universe. In addition, a spectrum of gravitational waves (tensor modes) is produced from the de Sitter vacuum [3].

Gravitational waves are very weakly coupled to matter, so once produced, they remain as a stochastic background until today, and thus provide a potentially important probe of the inflationary epoch. Detection of these primordial waves by using terrestrial wave detectors or the timing of millisecond pulsars [4] would indeed require an experimental sensitivity of several orders of magnitude beyond the current reach. However, like scalar perturbation, horizon-sized tensor perturbation induces large-scale temperature anisotropy of the cosmic microwave background (CMB) via the Sachs-Wolfe effect [5]. In addition, the tensor modes uniquely induce CMB  $B$ -mode polarization that is the primary goal of ongoing and future CMB experiments [6].

Recently, WMAP+SPT CMB data has placed an upper limit on the contribution of tensor modes to the CMB anisotropy, in terms of the tensor-to-scalar ratio, which is  $r < 0.18$  at 95% confidence level, tightening to  $r < 0.11$  when also including measurements of the Hubble constant and baryon acoustic oscillations (BAO) [7]. Planck Collaboration XVI has quoted  $r < 0.11$  using a combination of *Planck*, SPT, and ACT anisotropy data, plus WMAP polarization; however, the constraint relaxes to  $r < 0.26$  (95% confidence) when running of the scalar

spectral index is allowed with  $dn_s/d\ln k = -0.022 \pm 0.010$  (68%) [8]. More recently, BICEP2 CMB experiment has found an excess of  $B$ -mode power at degree angular scales, indicating the presence of tensor modes with  $r = 0.20^{+0.07}_{-0.05}$  and  $dn_s/d\ln k = -0.028 \pm 0.009$  [9]. If this result is confirmed, it would give a very strong support to inflation model and open a new window for probing the inflationary dynamics.

In this *Letter*, we investigate an another source for generating CMB  $B$ -mode polarization. The generated  $B$ -mode power spectrum can explain the BICEP2 excess  $B$ -mode power, while complying to the limit  $r < 0.11$  and  $dn_s/d\ln k = 0$ . Here we consider a nearly massless pseudoscalar  $\Phi \equiv M\phi$  that couples to the electromagnetic field strength via  $(-\beta/4)\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ , where  $\beta$  is a coupling constant and  $M$  is the reduced Planck mass. The effect of this coupling to CMB polarization has been previously studied [10–13]. It is well known that the above  $\phi$ -photon interaction may lead to cosmic birefringence [14] that induces rotation of the polarization plane of the CMB, thus converting  $E$ -mode into  $B$ -mode polarization [15, 16]. For such a pseudoscalar, we consider the contribution of  $\phi$  perturbation to cosmic birefringence.

We assume a conformally flat metric,  $ds^2 = a^2(\eta)(d\eta^2 - d\vec{x}^2)$ , where  $a(\eta)$  is the cosmic scale factor and  $\eta$  is the conformal time defined by  $dt = a(\eta)d\eta$ . The  $\phi F\tilde{F}$  term leads to a rotational velocity of the polarization plane of a photon propagating in the direction  $\hat{n}$  [14],

$$\omega(\eta, \vec{x}) = -\frac{\beta}{2} \left( \frac{\partial \phi}{\partial \eta} + \vec{\nabla} \phi \cdot \hat{n} \right). \quad (1)$$

Thomson scatterings of anisotropic CMB photons by free electrons give rise to linear polarization, which can be

described by the Stokes parameters  $Q(\eta, \vec{x})$  and  $U(\eta, \vec{x})$ . The time evolution of the linear polarization is governed by the collisional Boltzmann equation, which would be modified due to the rotational velocity of the polarization plane (1) by including a temporal rate of change of the Stokes parameters:

$$\dot{Q} \pm i\dot{U} = \mp i2\omega (Q \pm iU), \quad (2)$$

where the dot denotes  $d/d\eta$ . This gives a convolution of the Fourier modes of the Stokes parameters with the spectral rotation that can be easily incorporated into the Boltzmann code.

Now we consider the time evolution of  $\phi$ . Decompose  $\phi$  into the vacuum expectation value and the perturbation:  $\phi(\eta, \vec{x}) = \bar{\phi}(\eta) + \delta\phi(\eta, \vec{x})$ . For the metric perturbation, we adopt the synchronous gauge:  $ds^2 = a^2(\eta)\{d\eta^2 - [\delta_{ij} + h_{ij}(\eta, \vec{x})]dx^i dx^j\}$ . Neglecting the back reaction of the interaction, we obtain the mean field evolution as

$$\ddot{\bar{\phi}} + 2\mathcal{H}\dot{\bar{\phi}} + \frac{a^2}{M^2} \frac{\partial V}{\partial \bar{\phi}} = 0, \quad (3)$$

where  $\mathcal{H} \equiv \dot{a}/a$  and  $V(\phi)$  is the scalar potential. The equation of motion for the Fourier mode  $\delta\phi_{\vec{k}}$  is given by

$$\ddot{\delta\phi_{\vec{k}}} + 2\mathcal{H}\dot{\delta\phi_{\vec{k}}} + \left(k^2 + \frac{a^2}{M^2} \frac{\partial^2 V}{\partial \phi^2}\right) \delta\phi_{\vec{k}} = -\frac{1}{2} \dot{h}_{\vec{k}} \dot{\bar{\phi}}. \quad (4)$$

where  $h_{\vec{k}}$  is the Fourier transform of the trace of  $h_{ij}$ .

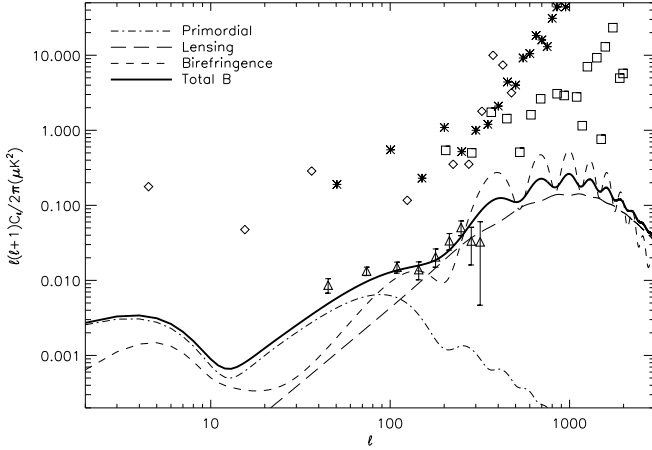


FIG. 1: Cosmological birefringence induced  $B$ -mode power spectrum through the perturbed nearly massless scalar field (short-dashed). Also shown are the theoretical power spectra of lensing induced  $B$  modes (long-dashed) and gravity-wave induced  $B$  modes (dot-dashed) with  $r = 0.11$ . The thick solid curve is the best-fitting averaged  $B$ -mode band powers that are the sum of these three  $B$ -mode power spectra convolved with the BICEP2 window function. Upper limits (95% c.l.) of QUAD (square), Quiet (asterisk), and WMAP9 (diamond), plus BICEP2 data (triangle) are shown.

If  $\phi$  is nearly massless or its effective mass is less than the present Hubble parameter, the mass term and the

source term in Eq. (4) can be neglected. In this case,  $V(\phi)$  can be either null or behaves just like a cosmological constant with  $\dot{\bar{\phi}} = 0$ . However, its perturbation is dispersive and can be cast into  $\delta\phi_{\vec{k}}(\eta) = \delta\phi_{\vec{k},i} f(k\eta)$ , where  $\delta\phi_{\vec{k},i}$  is the initial perturbation amplitude and  $f(k\eta)$  is a dispersion factor. For a super-horizon mode with  $k\eta \ll 1$ ,  $f(k\eta) = 1$ ; the factor then oscillates with a decaying envelope once the mode enters the horizon. Let us define the initial power spectrum  $P_{\delta\phi}(k)$  by  $\langle \delta\phi_{\vec{k},i} \delta\phi_{\vec{k}',i} \rangle = (2\pi^2/k^3) P_{\delta\phi}(k) \delta(\vec{k} - \vec{k}')$ . We solve for  $f(k\eta)$  numerically using Eq. (4) with  $\dot{\bar{\phi}} = 0$  and the initial power spectrum  $P_{\delta\phi}(k) = Ak^{n-1}$ , where  $A$  is a constant amplitude squared and  $n$  is the spectral index. The space-time background has no difference from that of the Lambda Cold Dark Matter model. Assuming a scale-invariant spectrum ( $n = 1$ ) and a combined constant parameter  $A\beta^2$ , the induced  $B$ -mode polarization is computed using our full Boltzmann code based on the CMBFast [17]. Note that both  $C_l^{TB}$  and  $C_l^{EB}$  power spectra vanish due to the fact that  $\langle \delta\phi \rangle = 0$ . We have tuned the value of  $A\beta^2$  to best fit the BICEP2 data as shown in Fig. 1. The likelihood plot in Fig. 2 shows the maximum likelihood value of  $A\beta^2 = 0.0072 \pm 0.0032$ , with 1-sigma error. We have also produced the rotation power spectrum [11, 18],

$$C_l^\alpha = \frac{\beta^2}{2\pi} \int dk k^2 \{ \delta\phi_k(\eta_s) j_l[k(\eta_0 - \eta_s)] \}^2, \quad (5)$$

where  $\eta_s$  denotes the time when the primary CMB polarization is generated on the last scattering surface or the rescattering surface. The rotation power spectra for the recombination and the reionization with  $A\beta^2 = 0.0072$  are shown in Fig. 3. Recently, constraints on direction-dependent cosmological birefringence from WMAP 7-year data have been derived, with an upper limit on the quadrupole of a scale-invariant rotation power spectrum,  $C_2^\alpha < 3.8 \times 10^{-3}$  [19]. Our quadrupole is within this limit. In fact, the limit should become weaker for our case because our  $C_l^\alpha$  scales as  $l^{-4}$  for  $l > 100$ .

Recently, the gravitational lensing  $B$ -mode polarization has been detected by cross correlating  $B$  modes measured by the SPTpol experiment with lensing  $B$  modes inferred from cosmic infrared background fluctuations measured by Herschel and  $E$  modes measured by SPT-pol [20]. Another CMB experiment called POLARBEAR has also confirmed this cross correlation [21]. However, we note that this detection has no constraint on the rotation-induced  $B$ -mode polarization because the rotation power spectrum and the lensing power spectrum are uncorrelated.

There have been physical constraints on  $A$  and  $\beta$ . Let us assume that inflation generates the initial condition for dark energy perturbation. Then,  $n \simeq 1$  and  $A \simeq (H/2\pi)^2/M^2$ , where  $H$  is the Hubble scale of inflation. The recent CMB anisotropy measured by the Planck mission has put an upper limit on  $A < 3.4 \times 10^{-11}$  [8]. This

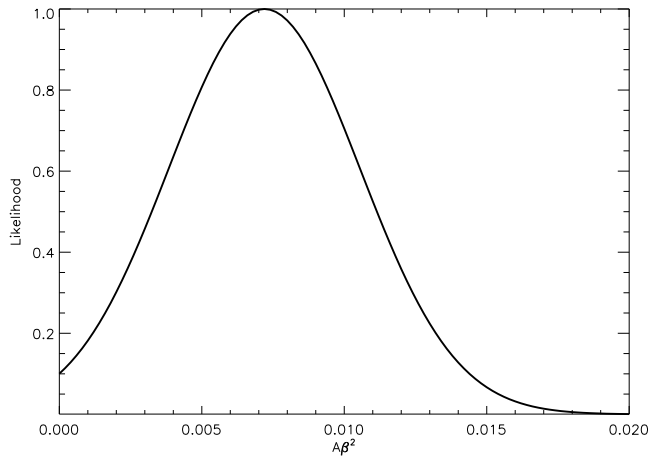


FIG. 2: Likelihood plot of the parameter  $A\beta^2$ . The maximum likelihood value with 1-sigma error is  $A\beta^2 = 0.0072 \pm 0.0032$ .

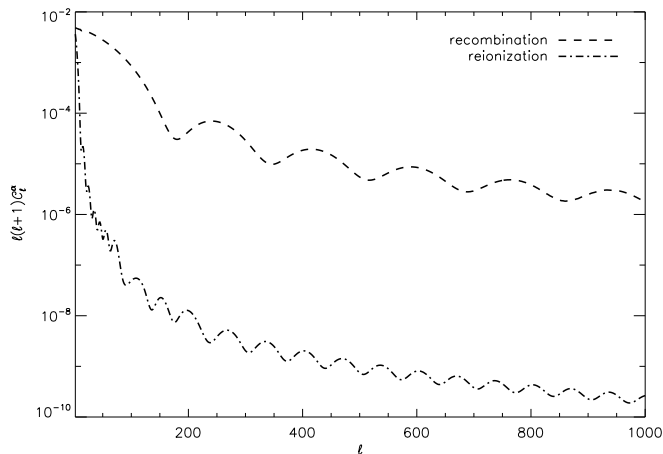


FIG. 3: Rotation power spectra for the recombination and the reionization with  $A\beta^2 = 0.0072$ .

implies that the present spectral energy density of dark energy perturbation relative to the critical energy density,  $\Omega_{\delta\phi} < 10^{-15}$ , which is negligible compared to that of radiation. The most stringent limit on  $\beta$  comes from the absence of a  $\gamma$ -ray burst in coincidence with Supernova 1987A neutrinos, which would have been converted in the galactic magnetic field from a burst of axion-like particles due to the Primakoff production in the supernova core:  $\beta < 2.4 \times 10^7$  for  $m_\phi < 10^{-9}\text{eV}$  [22]. Hence the combined limit is  $A\beta^2 < 2 \times 10^4$ , which is much bigger than the value that we have used here.

Cosmological birefringence perturbation can generate a rotation-induced  $B$ -mode power spectrum. The BICEP2 experiment may have firstly detected cosmological birefringence  $B$  modes at degree angular scales as proposed in this paper. It would be very important to make direct measurements of  $B$ -mode polarization at sub-degree scales where birefringence  $B$  modes can be mixed with lensing  $B$  modes. It thus poses a big challenge to do the separation of different  $B$ -mode signals. It is apparent that the rotation-induced  $B$ -mode has acoustic oscillations but to detect them will require next-generation experiments. In principle, one may use de-lensing methods [23] or lensing contributions to CMB bi-spectra [24] to single out the lensing  $B$  modes. Furthermore, de-rotation techniques can be used to remove the rotation-induced  $B$  modes [25]. More investigations along this line should be done before we can confirm the detection of the genuine  $B$  modes. Thus, it might be too hasty to conclude that many inflation models with small  $r$  are ruled out based on BICEP2 result. With the proper mechanisms like birefringence to induce the large-scale  $B$ -mode polarization, many inflation models can be still compatible with BICEP2 result.

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